Harnessing Earth's Green Guardians: Exploring Carbon Sequestration in Agricultural Practices

Abstract

The article for "Harnessing Earth's Green Guardians: Exploring Carbon Sequestration in Agricultural Practices" delves into the critical role of sustainable agriculture in mitigating climate change. It examines innovative farming techniques that enhance carbon sequestration, the process by which CO2 is captured and stored in the soil and biomass. By integrating practices such as cover cropping, agroforestry, and no-till farming, the research highlights how these methods can significantly reduce atmospheric carbon levels. The study underscores the dual benefits of these techniques, not only in improving soil health and crop yields but also in contributing to global efforts to curb greenhouse gas emissions. Through a combination of field experiments and modelling, the findings provide compelling evidence for policymakers and farmers to adopt these green practices, positioning agriculture as a pivotal player in the fight against climate change.

Keywords: captured, methods, reduce, adopt, crop

Introduction

Amidst growing worries about climate change, trees stand out as nature's quiet defenders, playing a crucial role in reducing the harmful effects of carbon emissions. Trees engage in the process of carbon sequestration, whereby they actively collect carbon dioxide from the atmosphere and store it inside their trunks, branches, and roots, effectively acting as guards against environmental pollution **[1]**. This inherent process not only assists in controlling the Earth's temperature but also makes a substantial contribution to our efforts to combat global warming. Trees, especially inside their vast forests, serve as carbon sinks, actively absorbing significant quantities of carbon dioxide during the process of photosynthesis. Trees undergo photosynthesis, a crucial process in which they use sunlight and carbon dioxide to produce oxygen and glucose **[2]**. Oxygen is released into the atmosphere, while carbon is stored in the trees' biomass. The carbon storage not only preserves the fragile equilibrium of greenhouse gases but also decreases the level of atmospheric carbon dioxide, a significant catalyst of climate change. Forests, due to their complex ecosystems, have an unsurpassed capacity to efficiently capture and store carbon **[3]**. The Amazon Rainforest, often known as the "lungs of the Earth," significantly contributes to the global carbon sink. Not only do large forests contribute, but urban trees and plants also play a part in storing carbon in local areas, enhancing the greenness and sustainability of cities. The significance of trees in carbon sequestration cannot be exaggerated **[4]**. With the ongoing release of historic levels of carbon into the atmosphere due to human activities, there is a growing need to save and rehabilitate forests. Implementing afforestation and reforestation programs, in addition to adopting sustainable forest management techniques, is vital for increasing the ability of trees to absorb and store carbon. In addition to their environmental effect, trees provide a wide range of advantages, including the promotion of biodiversity, prevention of soil erosion, and provision of important ecosystem services **[5]**. As we face the difficulties posed by climate change, it is crucial to acknowledge the essential role that trees play in capturing and storing carbon dioxide, which is a key aspect of responsible environmental management. Through promoting a worldwide dedication to reforestation initiatives and safeguarding current forests, we may use the influence of these environmentally conscious guardians in our joint endeavour to create a healthier and more harmonious planet **[6]**.

The carbon cycle is an essential element of Earth's system, facilitating the transfer of carbon between the atmosphere, hydrosphere, biosphere, and lithosphere. The soil plays a crucial role in this cycle, serving as a significant carbon sink that can store more carbon than both the atmosphere and all land-based plants combined **[7]**.

Soil carbon sequestration refers to the process of extracting CO2 from the atmosphere and storing it in the soil carbon pool, mostly via plant roots and microbes. This technique not only alleviates climate change by decreasing atmospheric CO2 levels but also improves soil quality and agricultural output **[8]**.

Nevertheless, the ability of soils to retain carbon is limited. The composition of the soil is impacted by several elements including soil type, climate, vegetation, and land management techniques. Soil disturbance caused by deforestation, intensive farming, or urbanization may result in the release of stored carbon into the atmosphere, so contributing to the greenhouse effect **[9]**.

Recent research has brought attention to the possibilities of 'carbon farming' - a variety of agricultural techniques designed to capture and store carbon in soils. Agroforestry, no-till farming, and the use of cover crops have shown the ability to enhance soil carbon reserves. Additionally, the use of organic amendments, such as compost and manure, might augment the soil's capacity to sequester carbon **[10]**.

The task at hand is to effectively manage and use soils in a manner that optimizes their ability to capture and store carbon. One must possess a comprehensive comprehension of soil carbon dynamics and formulate land management techniques that can preserve and augment soil carbon stores. Through meticulous management, soils may persist in their crucial function of moderating climate change, despite the fragile equilibrium involved **[11, 12]**.

Fig 1. Emission biotechnologies

<u>How soil affect carbon cycle</u>

Gaining a comprehensive comprehension of the functioning and composition of soil is essential for grasping the intricacies of the global carbon cycle and the phenomenon of climate change **[13]**. The destiny of organic matter in the soil establishes a connection between soils and both the atmosphere and the ocean, which are the primary global carbon sinks. In order to address this inquiry, we turn our attention to the realm of plants. During photosynthesis, plants function as carbon dioxide conduits, extracting CO2 from the atmosphere and converting it into biomass, including wood, roots, and leaves **[14]**. "Plants are the primary agents for introducing carbon into the soil," Cusack said. Trees, specifically, extract substantial quantities of carbon dioxide from the atmosphere and function as natural safeguards against climate change caused by greenhouse gases **[15]**.

Organic matter is formed when plants, plant parts, and other creatures die. The soil microbes secrete enzymes that decompose these creatures into recyclable nutrients and smaller carbon molecules. Certain carbon molecules nourish other soil organisms, while others collect in the soil and adhere to its structure **[16]**. Some of these compounds are released as carbon dioxide into the atmosphere and subsequently absorbed by the ocean, thereby linking soils to the global carbon cycle. When carbon is stored in the soil, it gets sequestered, meaning it is sealed away, and it may stay stable there for millions of years if left undisturbed **[17]**. The reason soil is referred to be a carbon sink is because it has the ability to store carbon. The storage of soil carbon varies throughout various biomes according to climatic conditions. "Tropical soils and sub-Arctic permafrost soils have the highest carbon storage capacity, but they differ significantly in their storage mechanisms," Cusack said Mongabay **[18]**. "The fertile soils in tropical regions, characterized by extensive clay surfaces, have effectively sequestered carbon. The carbon, initially present in plant roots, has been gradually transferred into the deeper layers of the soil." Cusack and her colleagues at Lawrence Livermore National Lab in California have using radiocarbon dating to approximate the mean age of carbon in tropical soils. In the northern regions, namely in areas with permafrost, the soil has been frozen for thousands of years **[19]**. As a result, plant matter that has been deposited there has not undergone decomposition and has stayed frozen, creating a significant reservoir of terrestrial carbon. Organic stuff is located at such a great depth that carbon does not undergo any turnover. "It is simply immobilized in the soil," Cusack said **[20]**.

Kind of carbon sequestration

Carbon sequestration is the process by which carbon dioxide is captured and stored to prevent it from being released into the atmosphere.

Carbon sequestration operates in the following manner:

1. **Biological sequestration**

Biological sequestration refers to the process of capturing and storing carbon dioxide via natural biological processes. Biological activities, especially those carried out by trees and plants, are crucial in carbon sequestration, which helps to reduce the impact of climate change **[21]**. Photosynthesis is a remarkable process where these green guardians naturally take in carbon dioxide (CO_2) from the environment and simultaneously produce oxygen, which is essential for life. Photosynthesis is the process by which plants use sunlight to transform carbon dioxide (CO_2) into oxygen and carbon, which is then stored in their biomass. Forests, which function as large carbon sinks, are emerging as unacknowledged heroes in the fight against climate change **[22]**. Their tall and extensive canopies, together with their large areas of foliage, efficiently absorb substantial quantities of carbon, essentially isolating it from the atmosphere. Biological sequestration helps decrease the concentration of CO_2, a significant greenhouse gas, and supports the establishment and preservation of a stable and sustainable environment **[23]**. Forests possess an innate capacity to store significant amounts of carbon, making them very helpful in our efforts to counterbalance carbon emissions caused by human activities. It is crucial to acknowledge the significance of conserving and repairing these natural carbon storage areas **[24]**. As we deal with the challenges of climate change, it is crucial to prioritize the well-being and ability to recover of ecosystems in order to achieve a sustainable future. The process of biological sequestration, which is facilitated by the efficient functioning of trees and plants, demonstrates how nature has the solution to reducing the effects of human activities on our world **[25]**.

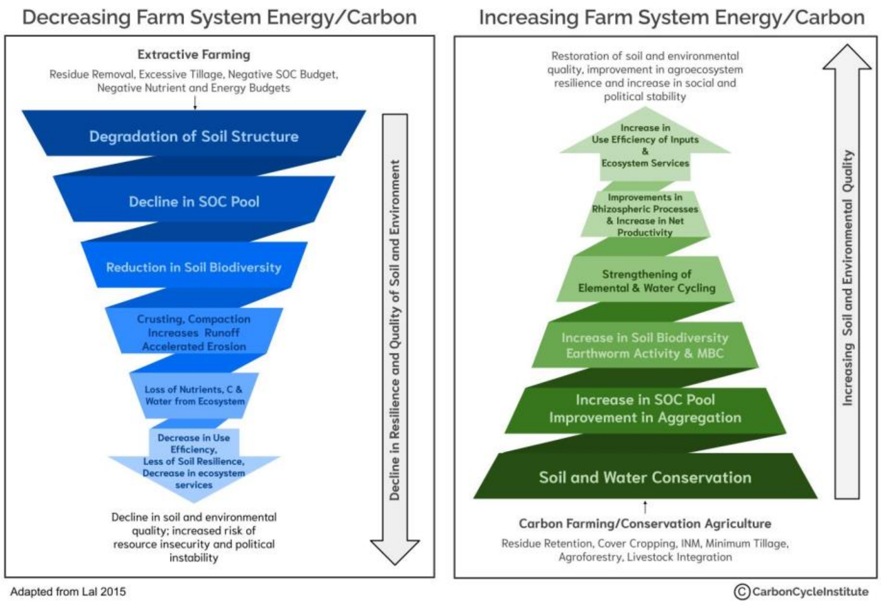

Fig 2. Farm system energy

2. **Soil Sequestration**

Soil Sequestration refers to the process of storing carbon dioxide in the soil. Soil sequestration is a valuable asset in efforts to combat climate change and promote sustainable agriculture. Utilizing targeted agricultural methods such as cover cropping and agroforestry plays a crucial role in improving the capture and storage of carbon in soils **[26]**. The magic resides in the capacity of fertile soils to sequester carbon for long periods, offering a dual advantage of reducing climate change and promoting sustainable agriculture practices. Cover cropping is the practice of planting supplementary crops during periods when the main crops are not growing, with the aim of protecting the soil from erosion and reducing the loss of nutrients **[27]**. This not only improves soil fertility but also promotes the uptake and sequestration of carbon dioxide. Agroforestry is an agricultural practice that combines trees and shrubs with conventional farming practices to create a harmonic synergy. Trees not only absorb carbon but also provide ecological benefits, including biodiversity preservation and enhanced water retention **[28]**. The importance of soil sequestration goes beyond its environmental effects. It plays a role in the development of robust agricultural systems, fostering long-term viability. As we explore these methods, we discover a route towards a more environmentally friendly and enduring future, where the soil underneath us becomes a vital contributor in worldwide endeavours to address climate change and guarantee food stability **[29]**.

3. **Geological Sequestration**

Geological Sequestration refers to the process of storing carbon dioxide underground in geological formations. CCS technology in industrial processes and power plants intercepts CO2 emissions prior to their release into the atmosphere. The carbon that has been caught is then transported and deposited underground in geological formations, so limiting its release into the atmosphere **[30]**.

4. **Ocean sequestration**

Ocean sequestration refers to the process of storing carbon dioxide in the ocean. This approach entails introducing items, such as pulverized rocks, into the water to augment its alkalinity. This process boosts the inherent capacity of the ocean to assimilate and retain carbon dioxide (CO2), hence reducing the adverse effects of ocean acidification **[31]**.

Atmosphere CO_2

During the last three centuries, there has been a substantial alteration in atmospheric CO2 concentrations, surpassing 100 parts per million (ppm) in only 250 years. The present concentration level exceeds 400 parts per million (ppm), far beyond the approved threshold of 350 ppm. Over the last ten years, the concentration of atmospheric CO_2 has risen by more than 2 parts per million every year, reaching a current level of 413.08 ppm **[32]**. During the Triassic-Jurassic mass extinction, volcanic activity caused CO_2 levels to reach 4400 ppm in the ancient past. China now represents almost 26% of worldwide emissions, whilst the USA, India, and Russia provide emission percentages of 13.7, 7.0, and 4.8 correspondingly. Each year, around 51 billion tons of greenhouse gases are emitted into the environment **[33]**. The objective is to reduce the number to zero. Climate change has led to a gradual rise in sea level and the average world temperature. Since 1880, the Earth's average temperature has risen by 0.8 °C, resulting in an increase in the global mean sea level. The increase in sea levels would result in the inundation of densely populated coastal regions, such as Bangladesh, and exert strain on available land to accommodate the expanding population of 9.6 billion by 2050. Intensive efforts are required to eliminate these dangerous forecasts **[34]**.

<u>Capturing of carbon</u>

Carbon capture is an essential component of energy generation, especially when it comes to burning fossil fuels. The two primary methods for carbon capture are the Integrated Gasification Combined Cycle (IGCC) and Integrated Reformed Combined Cycle (IRCC). IGCC is a technique that removes carbon from coal before it is burned, while IRCC combines a gasification process with a power producing unit **[35]**. In Integrated Gasification Combined Cycle (IGCC), the process involves removing carbon from coal before it is burned. Coal or other carbon-based materials are utilized as inputs in this process. The syngas is produced by the water-gas shift (WGS) process, which transforms carbon monoxide (CO) into carbon dioxide (CO_2). The generated heat is transferred to the Heat-Recovery Stream Generator (HRSG), leading to the production of a fuel that is free from carbon emissions **[36]**. Post-combustion capture refers to the process of collecting carbon dioxide from the exhaust gases produced by power stations that burn fossil fuels. The technique described is the only approach now utilized in industry, using multiple technologies including solvent-based absorption, membrane-separation, mineralization, adsorption-driven, cryogenic capture, and microalgae-based carbon capture **[37]**. Within the category of solvent-based post-combustion carbon capture (PCC), amine-based solvents are extensively used, with monoethanolamine (MEA) being the most prevalent due to its exceptional reactivity towards CO_2 and its ability to efficiently collect it. Membranes are selectively permeable structures that segregate CO_2 from the gaseous mixtures produced during fuel burning. Membrane-based PCC offers substantial benefits because to its ability to cover large surface areas, resulting in a notable reduction in equipment size and an increase in efficiency **[38]**. Polytetrafluoroethylene (PTFE) is the predominant PCC membrane used in several pilot experiments. Mineralization refers to the process of converting CO_2 into stable carbonates for the purpose of storing it, particularly in regions that do not have appropriate geological formations. Additionally, it is more ecologically sustainable than geologic sequestration **[39]**. Adsorption is the method of capturing CO_2 by causing it to interact with a solid or chemical adsorbent, such as altering inexpensive carbons using polyethyleneimine. Ionic solvents have shown superior adsorption capabilities compared to other substances, mostly owing to their ease of regeneration, less solvent loss, and reduced environmental effect **[40]**. Nanomaterials, including nanomembranes, nanoparticles, and nanosheets, are increasingly becoming recognized and accepted globally as substances that may adsorb other substances. Additional materials, including as activated carbon, zeolites, amine-functionalized silica, porous organic frameworks, and metal organic frameworks (MOFs), are broadening the selection of adsorbent materials for post-combustion capture **[41]**.

Oxy-combustion capture is a process that does not involve actual "capture" of CO_2. The fossil fuel is combusted in an atmosphere with a high concentration of oxygen, resulting in a more efficient and complete combustion process. This significantly decreases the levels of carbon monoxide (CO) and sulphur dioxide (SO_2) emissions. The procedure does not use membranes or absorbents and is very cost-effective for new plants. However, the cost rises when retrofitting existing plants **[42]**. The cost of carbon capture is lower in oxy-combustion capture compared to other methods. Another benefit is that almost pure (90%) CO2 may be compressed and stored straight without requiring further purification, as is the case with PCC. The study revealed that membrane-based CO2 capture devices incur a higher energy penalty compared to amine- and ammonia-based systems **[43]**. Chemical looping combustion (CLC) is an alternative technique for carbon capture that entails transforming the carbon dioxide produced by the fuel into a gaseous form. The process exhibits higher efficiency and more environmental friendliness compared to conventional techniques. However, it faces obstacles such as the need to modify older plants owing to elevated temperatures during combustion and the ingress of air leaks into the system, which adversely impact its performance **[44]**.

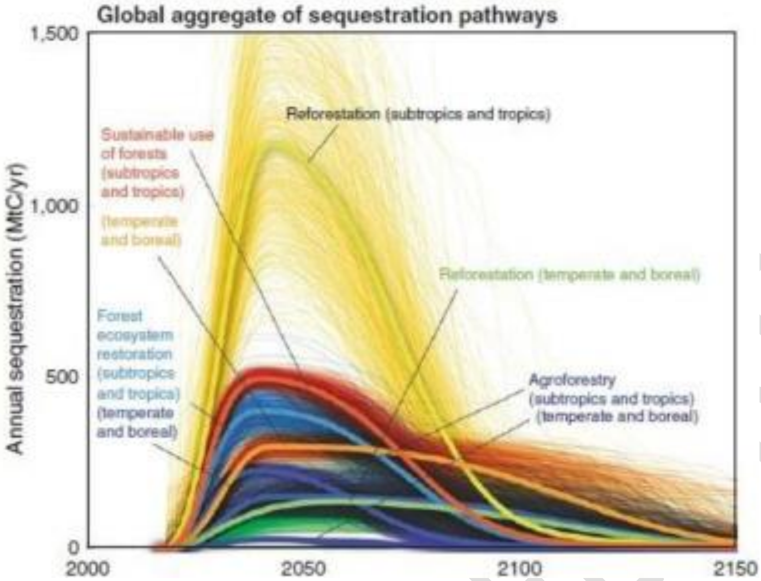

Fig 3. Global aggregate of sequestration pathways

<u>Comprehension of the Carbon Sequestration Process</u>

A method that involves absorbing and storing carbon dioxide from the atmosphere is referred to as carbon sequestration. When applied to the field of agriculture, this refers to the implementation of methods that improve the capacity of soil and plants to take in and store carbohydrates. Cover cropping, no-till farming, and agroforestry are examples of sustainable agricultural practices that play a very important role in this process **[45]**. These techniques enhance the structure of the soil, raise the amount of organic matter present, and encourage biodiversity, all of which lead to an increased ability to store carbon **[46]**.

<u>Making a Cover Crop</u>

On the other hand, cover cropping refers to the practice of growing certain crops during off-seasons in order to cover the soil rather than leaving it naked. The fertility of the soil is improved, erosion is reduced, and water retention is enhanced by these crops, which are often grasses or legumes. Because they contribute to the accumulation of organic matter in the soil, cover crops are an essential component of sustainable agriculture because they play a significant part in the process of carbon sequestration **[47]**.

<u>A plain covered in buckwheat</u>

The concept of cover cropping, which is shown here with a field of buckwheat, improves the fertility of the soil and sequesters carbon, therefore encouraging sustainable agricultural methods.

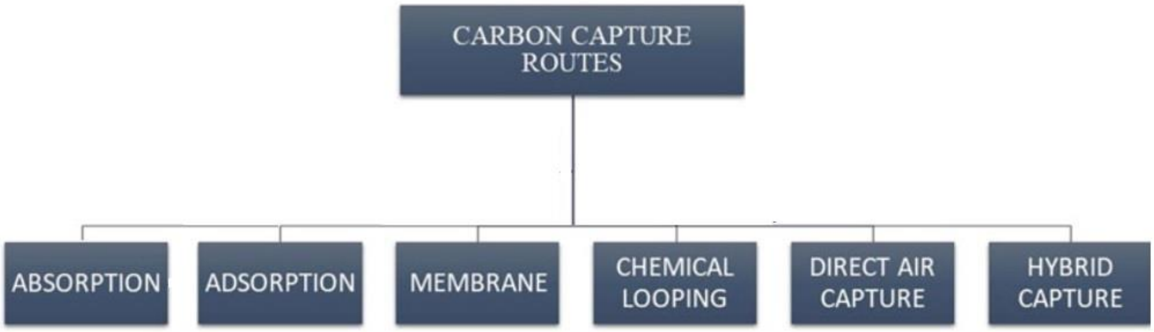

Fig 4. Carbon capture routes

<u>Farming without tilling the soil</u>

The practice of no-till farming reduces the need for ploughing, which both messes up the structure of the soil and releases carbon that has been stored. In its place, seeds are drilled straight into soil that has not been disturbed. In addition to preventing soil erosion and improving water infiltration, this approach helps to preserve the integrity of the soil. The practice of farming without tilling the soil is an essential component of carbon farming, which is in perfect harmony with the principles of sustainable agriculture **[48]**.

<u>Agroforestry and the Advantages It Offers</u>

Integrated and sustainable land-use systems may be created via the practice of agroforestry, which mixes agriculture with forestry. Farmers are able to increase biodiversity, improve soil health, and sequester carbon, all of which may be accomplished by introducing trees into agricultural settings. As a result of photosynthesis, trees are able to take up carbon dioxide and store it in their biomass and soil. This not only helps to reduce the effects of climate change, but it also offers other advantages, such as providing shelter from the wind and shade, as well as providing a variety of habitats for fauna **[49]**.

<u>Cutting in the Alley</u>

The cultivation of crops in the space between rows of trees or shrubs is an example of a special form of agroforestry known as alley cropping. This method achieves the highest possible efficiency in land usage and encourages the storage of carbon. Through the accumulation of leaf litter and the rotation of roots, trees provide a consistent supply of organic matter to the soil, so replenishing it with carbon. The practice of alley cropping is a prime example of how carbon farming ideas may be efficiently integrated into sustainable agriculture **[50]**.

<u>The use of silvopasture</u>

With silvopasture, trees, pasture, and cattle are all brought together on the same piece of ground. The increased biomass and root growth that this method provides contributes to an increase in carbon sequestration. It is beneficial for cattle to have trees because they provide shade and fodder, and their deep roots serve to maintain the soil and trap carbon. The concept of silvopasture exemplifies the many advantages that may be gained by integrating carbon farming with environmentally responsible agricultural methods **[51]**.

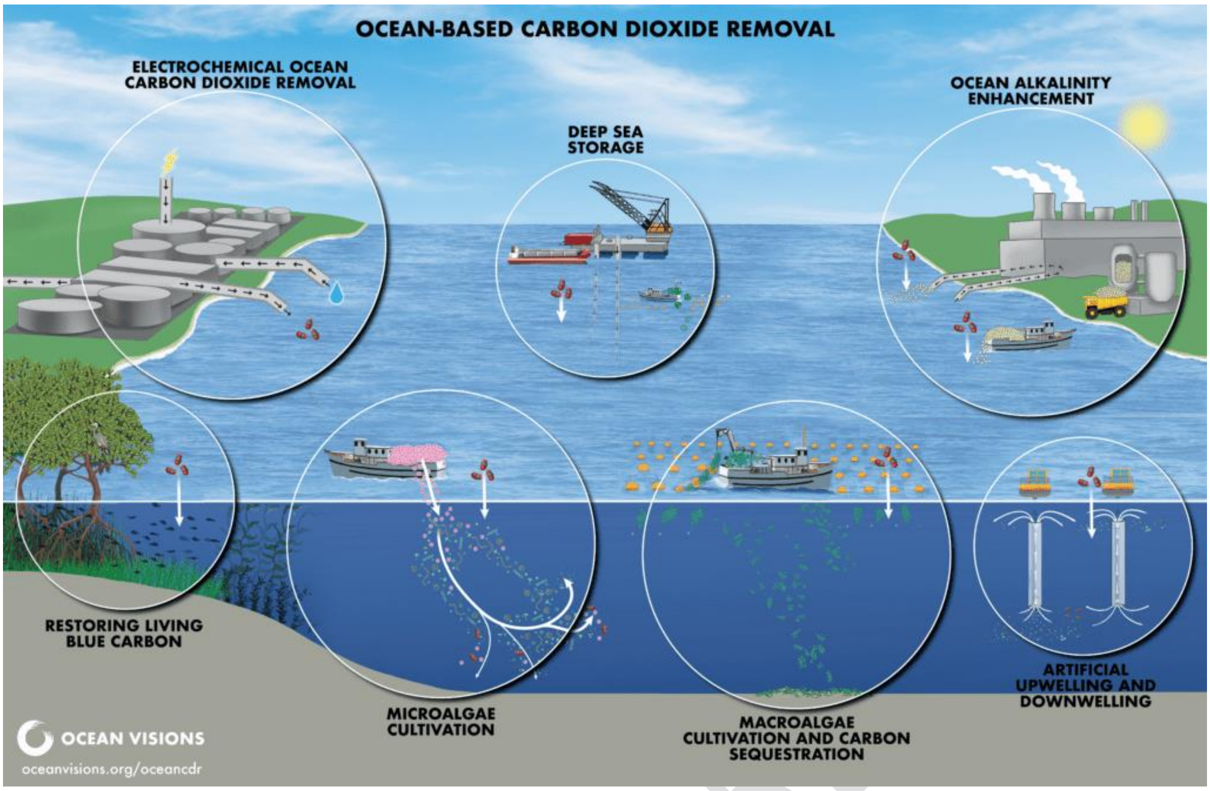

Fig 5. Ocean-based carbon dioxide removal

What Function Do Perennial Crops Serve

Another effective tool for carbon farming is the cultivation of perennial crops, which may be grown for a number of years without the need for replanting. In contrast to annual crops, which need to be tilled and planted on a regular basis, perennials have extensive root systems that are capable of storing carbon and improving the structure of the soil. Examples of such trees are nut trees, fruit trees, and grasses that grow every year. The reduction of soil disturbance and the enhancement of resistance to climatic extremes are two ways in which these crops provide a contribution to sustainable agriculture **[52]**.

Grain that is perennial

In order to take the place of annual crops like wheat, researchers are working on developing perennial grains like Kernza. The root systems of these grains are vast, which contributes to the sequestration of carbon and the improvement of soil health. Farmers are able to lessen the impact that food production has on the environment and develop sustainable agricultural practices by introducing perennial grains into cropping systems **[53]**.

Forages that are perennial

Forages that are perennial, such as alfalfa and clover, tend to produce ground cover for an extended period of time and help sustain livestock output. Carbon is stored in their deep roots, which also improves the fertility of the soil. Through the enhancement of ecosystem services and the promotion of carbon sequestration, the incorporation of perennial forages into agricultural systems is designed to correspond with the aims of sustainable agriculture **[54]**.

Carbon farming techniques

Organization of Forests

In addition to being a significant source of greenhouse gas (GHG) sequestration, healthy forests are also capable of absorbing and storing carbon dioxide emissions that are generated by other sources.

Carbon offsets may be produced via a number of methods, such as preventing deforestation and permanently conserving land, engaging in activities that include regeneration and replanting, and improving forest management **[55]**.

Managing forests by thinning them out, selectively harvesting trees, encouraging regrowth, planting new trees, and using fertilisers to help forests grow in a productive and sustainable way are some of the activities that can be done to address the issue of deforestation, which contributes to 15-20% of the rise in greenhouse gas levels globally. Agroforestry not only helps farmers achieve additional sources of income, but it also helps sequester carbon **[56]**.

<u>Grassland preservation strategies</u>

Greenhouse gas (GHG) absorption and sequestration may be accomplished via the utilization of native grasses and other types of plants as a natural source. Carbon offsets that fall into this category are centred on the preservation of native plant life via the permanent protection of land and the avoidance of land conversion for the purpose of commercial development or intensive agriculture **[57]**.

<u>Producing Energy from Renewable Sources</u>

In the power grid, carbon offsets are produced by renewable energy facilities such as wind and solar power plants. These facilities create carbon offsets by substituting fossil fuel-based electricity generation sources.

This carbon credit is held by the organization that is responsible for the development of the project, and it is generated by the carbon offsets that are produced from a certified third-party project **[58]**.

<u>Methods of Agriculture That Conserve Resources</u>

The use of techniques like as crop rotation, cover cropping, zero tillage, and crop residue management helps to reduce the amount of soil disturbance while simultaneously encouraging the formation of organic matter. The practice of planting cover crops during fallow times in order to conserve and improve the soil, increase biodiversity, and sequester carbon are all beneficial **[59]**.

<u>Grazing that is Rotational</u>

It is a strategy that involves moving cattle to new pastures on a regular basis. This provides previously grazed regions with the opportunity to regenerate, so reducing the amount of erosion that occurs and encouraging vigorous regrowth.

As a result, the thriving plant is able to take up carbon dioxide from the air and store it in the soil via the process of photosynthesis **[60]**.

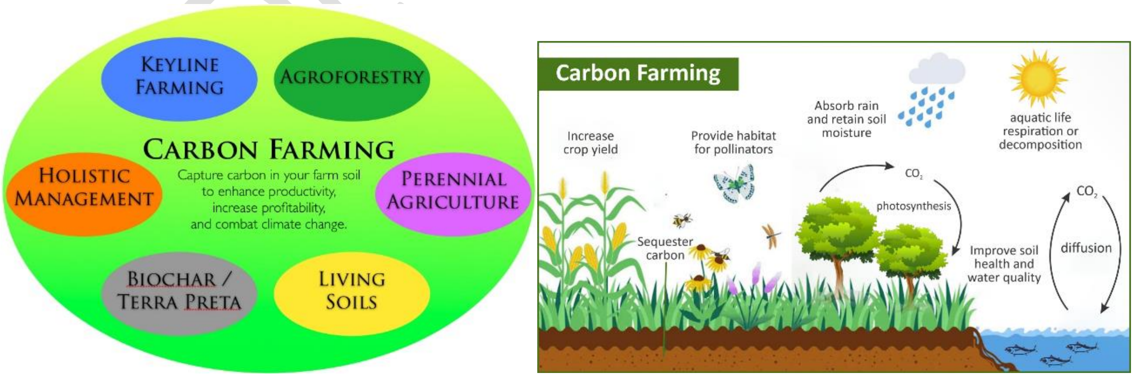

Fig 6. Carbon farming

Role of soil in carbon sequestration

<u>Comprehending the Role of Soil in the Carbon Cycle</u>

The carbon cycle is an essential element of Earth's system, facilitating the transfer of carbon between the atmosphere, hydrosphere, biosphere, and lithosphere. Soil plays a crucial role in this cycle by serving as a significant carbon sink, capable of storing more carbon than both the atmosphere and all land vegetation combined **[61]**.

Soil carbon sequestration refers to the process of extracting CO2 from the atmosphere and storing it in the soil carbon pool, mostly via plant roots and microbes. This technique not only alleviates climate change by decreasing atmospheric CO2 levels but also improves soil quality and agricultural output **[62]**.

Nevertheless, the ability of soils to retain carbon is limited. The composition of the soil is impacted by several variables, including soil type, climate, vegetation, and land management techniques. Soil disturbance caused by deforestation, intensive farming, or urbanization may result in the release of stored carbon into the atmosphere, so contributing to the greenhouse effect **[63]**.

Recent research has brought attention to the possibilities of 'carbon farming' - a variety of agricultural techniques designed to capture and store carbon in soils. Agroforestry, no-till farming, and the use of cover crops have shown the ability to enhance soil carbon reserves. Additionally, the use of organic additions, such as compost and manure, might augment the soil's capacity to retain carbon **[64]**.

The task at hand is to effectively manage and use soils in a manner that optimizes their capacity to capture and store carbon. Acquiring a comprehensive understanding of soil carbon dynamics and formulating land management techniques that can preserve and augment soil carbon reserves are necessary for this. Through meticulous stewardship, soils may persist in their crucial function of moderating climate change, despite the fragile equilibrium involved **[65]**.

<u>The Relationship between Greenhouse Gases and Soil</u>

Soils constitute a substantial contributor to greenhouse gas emissions, yet their interaction with the environment is intricate and diverse. The main greenhouse gases linked to soils are carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), each fulfilling a distinct function in the climate system **[66]**.

Soil releases carbon dioxide during the process of organic matter decomposition. Although it is a natural occurrence in the carbon cycle, human actions such as deforestation and inappropriate land use may expedite this process. Methane, a greenhouse gas with a higher potency than CO2, is generated in oxygen-deprived environments, which are often seen in wetlands and rice paddies. Nitrous oxide, a potent greenhouse gas, is emitted from soils as a result of nitrification and denitrification microbiological processes. The excessive use of nitrogen fertilizers in agriculture may intensify these processes **[67]**.

The release of these gases from soils is affected by several variables, such as temperature, moisture, soil type, and land management methods. Wetter circumstances may cause methane emissions to rise, while warmer temperatures can speed up the breakdown of organic materials, resulting in greater CO2 emissions **[68]**.

Current studies have prioritized comprehending these discharges within the framework of global climate change. Research has shown that modifying land management strategies, such as enhancing irrigation efficiency, using conservation tillage, and employing precision farming techniques, may effectively decrease the release of these gases from soils **[69]**.

To effectively reduce greenhouse gas emissions from soil, it is crucial to use soil management practices that preserve the ecological equilibrium of the soil. This include the safeguarding of natural ecosystems, the rehabilitation of damaged lands, and the adoption of sustainable agriculture methods that not only decrease emissions but also improve the soil's inherent capacity to capture and store carbon **[70]**.

<u>Focuses on agricultural practices and their effects on soil health.</u>

Agriculture has a significant influence on the health of soil and its capacity to serve as a reservoir for carbon. Conventional farming methods, such as extensive ploughing, planting just one kind of crop, and excessive use of chemical fertilizers and pesticides, may result in the deterioration of soil quality, erosion, and depletion of organic matter. Consequently, this diminishes the soil's ability to retain carbon **[71]**.

On the other hand, sustainable farming techniques have the ability to improve the arrangement of soil particles, promote a greater variety of living organisms, and raise its capacity to store carbon. Practices like as crop rotation, cover cropping, and decreased tillage contribute to the preservation of soil quality, erosion prevention, and the enhancement of organic matter **[72]**.

Crop rotation is a farming practice that entails cultivating various varieties of crops consecutively on the same piece of land to enhance soil quality and minimize reliance on chemical fertilizers. Cover crops, such as legumes and grasses, are sown during periods of inactivity to safeguard the soil against erosion and replenish it with organic material via decomposition. Tillage reduction or no-till farming practices aim to minimize soil disruption, therefore protecting soil structure, saving moisture, and sustaining carbon-rich organic matter **[73]**.

Implementing these sustainable techniques not only has positive implications for the environment but also for farmers. Optimal soil conditions may result in increased agricultural productivity, less reliance on chemical additives, and enhanced ability to withstand and recover from more frequent severe weather events associated with climate change **[74]**.

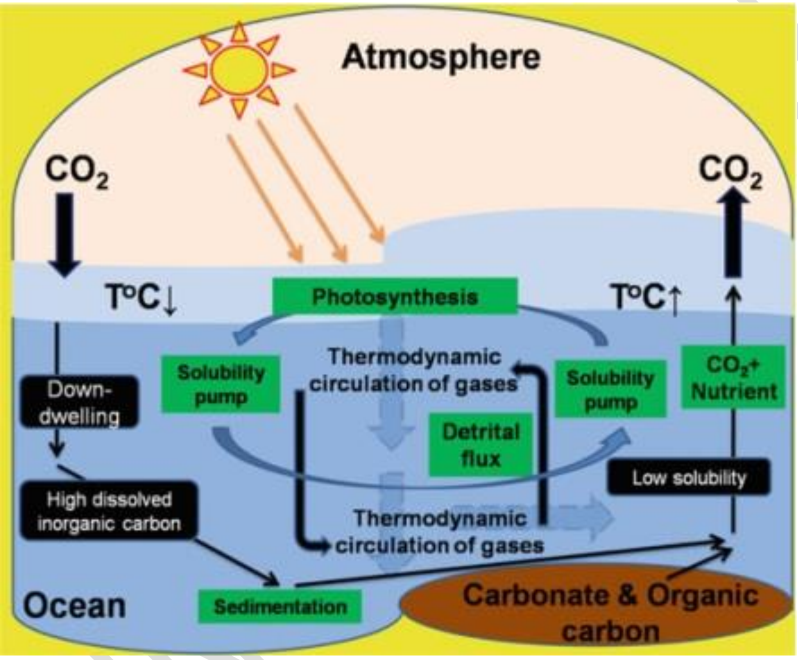

Fig 7. sustainable techniques

<u>Focuses on soil management strategies aimed at mitigating climate change.</u>

Efficient soil management is crucial for climate mitigation. Methods that increase the amount of carbon stored in soil may greatly contribute to the reduction of atmospheric CO2 concentrations. A approach that may be used is the use of Premium Engineered Biochar, which is a stable form of carbon that is created by the thermal breakdown of organic material in an atmosphere with minimal oxygen. Biochar has the ability to retain carbon in the soil for extended periods of time, ranging from hundreds to thousands of years **[75]**.

Agroforestry, which involves incorporating trees and shrubs into agricultural landscapes, is a strategy

that may enhance the process of storing carbon in soils. Both trees and shrubs sequester carbon in their biomass and enhance soil organic matter via the shedding of leaves and branches **[76]**.
Organic agricultural techniques, which refrain from using artificial fertilizers and pesticides, may help improve the retention of carbon in the soil. Organic systems often exhibit elevated amounts of soil organic matter, enhanced soil structure, and increased water infiltration, all of which together lead to a larger capacity for carbon sequestration. The soil management approaches have shown great promise, as shown by success stories from many parts of the globe. Costa Rica, for instance, has shown that agroforestry systems had a greater capacity for carbon storage compared to traditional agricultural systems or pasturelands. Moreover, the implementation of no-till farming across the American Midwest has resulted in elevated soil carbon levels and enhanced soil health **[77]**.

Focuses on advancements in the field of soil science

The discipline of soil science is progressing quickly, as emerging technologies provide more profound understandings of soil health and its function within the climate system. Advancements such as precise, handheld, and portable systems for instantly testing and monitoring soil and water, along with satellite imagery, are empowering scientists and farmers to closely track soil moisture, pH levels, electrical conductivity, and all major and minor nutrient levels, as well as various forms of carbon content, weather conditions, and AI-driven recommendations, with unparalleled accuracy **[78]**. Precision agriculture, using technology to customize soil and crop management based on the unique characteristics of each land parcel, is fundamentally transforming our agricultural practices. For example, drones are now used to survey and analyse soil variability across extensive regions, enabling precise treatments that enhance soil health and carbon sequestration **[79]**. The potential for these technologies in the future is immense. Machine learning algorithms are now being created to forecast the potential for soil carbon sequestration. This might be beneficial for devising and executing soil management policies on a worldwide level. These technological developments not only facilitate research but also have tangible applications. They have the ability to assist farmers in making well-informed choices that enhance soil health, boost production, and aid in the mitigation of climate change **[80]**.

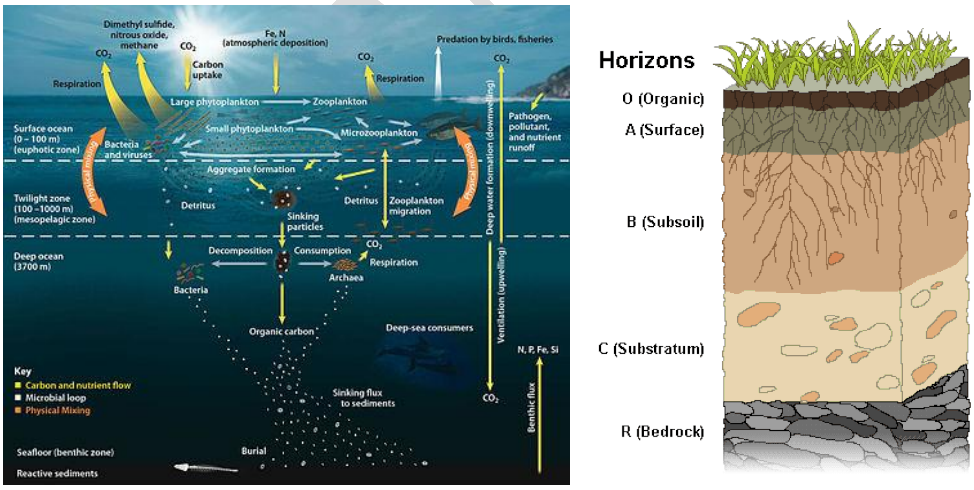

Fig 8. Advancements in the field of soil science

Focuses on the policy and measures used to protect soil.

Policy frameworks are essential for the conservation and management of soil. The management of soils over wide regions is significantly influenced by current policies, such as the European Union's Common Agricultural Policy (CAP). Nevertheless, it is often necessary to ensure that these regulations are more closely harmonized with the most recent scientific findings about soil health and climate change **[81]**.

Existing laws are criticized for lacking sufficient incentives to encourage farmers to adopt sustainable practices, inadequate safeguards to safeguard soil biodiversity, and insufficient money for research on soil health. Policy proposals include the incorporation of soil carbon sequestration into carbon trading programs, promoting the shift towards sustainable farming methods, and safeguarding crucial natural habitats that are essential for soil health **[82]**.

Global treaties, including the Paris Agreement, acknowledge the significance of soil health in mitigating climate change. To align with international commitments, national policy might implement specific goals for the sequestration of soil carbon and develop systems for monitoring and reporting **[83]**.

<u>Focuses on the involvement of both the community and individuals in taking action.</u>

Policy and innovation are crucial factors, but community and individual efforts are equally vital in enhancing soil health and addressing climate change. Community gardens, urban agricultural programs, and local conservation projects have the potential to enhance soil health **[84]**.

Individuals may promote local, sustainable agriculture by making conscious purchase decisions, engaging in community composting initiatives, and fighting for regulations that safeguard soil health. Education and awareness initiatives may also empower people to engage in acts that promote soil health, such as minimizing food waste and refraining from the use of detrimental pesticides in home gardening **[85]**.

Community-driven endeavours, such as the transition town's movement and permaculture projects, have shown the capacity of local efforts to provide substantial environmental advantages, such as enhanced soil quality and heightened carbon sequestration **[86]**.

Potential benefits

The deterioration of the soil's health and the narrowing of the earnings available to farmers are two of the most significant problems facing Indian agriculture. Since the Green Revolution, there has been a significant increase in the use of fertilizers and pesticides, which has led to a decrease in the amount of carbon in the soil and, as a consequence, a decline in the quality of the soil. It is believed that almost thirty percent of India's total land area, of which almost half is used for agricultural purposes, has been degraded, especially in regions that are influenced by rainfall **[87]**.

The adoption of sustainable farming techniques by farmers not only allows them to increase their revenue via the sale of carbon credits, but it also helps them enhance the health of their soil, the yield of their crops, the productivity of their land, and their profitability. The optimization of water consumption, the adoption of precision agricultural technologies to decrease inputs, the reduction of greenhouse gas emissions, and the improvement of soil fertility are all examples of approaches that are considered sustainable **[88]**. Productivity may be increased, crop losses can be avoided, and real-time insights can be obtained for improved land management via the use of techniques such as managing crop residue in situ, optimizing water consumption in rice production, deploying farm mechanization, drones, and satellite imagery **[89]**. Water optimization strategies that make use of bio-stimulants or drip irrigation systems are essential components of sustainable agriculture. Soil wellness programs that are centred on increasing the organic carbon content of the soil, activities that reduce carbon emissions while simultaneously boosting carbon absorption, and other factors are also essential. Not only does the agricultural sector have the capacity to cut emissions, but it also has the potential to become a net carbon sink if it adopts sustainable farming techniques **[90]**. To encourage broad adoption of sustainable methods, grassroots-level activities are required. These programs should educate farmers on the advantages of sustainable farming, enable the exchange of knowledge within communities, and make technology and mechanization available to all. In light of the fact that the demand for carbon credits is expected to rise by a factor of fifteen by the year 2030, agritech businesses have to provide farmers with the tools they want and make it easier for them to acquire and sell carbon credits **[91]**.

Monitoring the levels of carbon in the soil and providing incentives for its improvement are both essential components of improving the health of the soil. The amounts of greenhouse gases that are prevented from entering the atmosphere or removed from it are represented by carbon credits. Carbon sequestration and the subsequent sale of carbon credits are two ways in which farmers may generate income **[92]**. The values of carbon credits fluctuate based on the market rates and the amount of carbon that is sequestered. The adoption of regenerative methods by farmers may result in the sequestration of one to four carbon credits per acre, which in turn leads to benefits in soil health. These advantages include greater water-holding capacity, better nutrient availability, enhanced water infiltration, decreased soil density, and lower soil surface temperature. In addition to the increased cash that farmers get, there are other advantages that come with participation in carbon offset schemes **[93]**. Among them are the reduction of greenhouse gas emissions via carbon sequestration, the enhancement of soil health that leads to greater agricultural yields and water retention, the preservation of biodiversity, the use of land in a sustainable manner, and the development of rural areas through the creation of employment and income-generating possibilities. However, in order to fully appreciate these advantages, there are a number of obstacles that need to be overcome **[94]**.

<u>Challenges in carbon sequestration</u>

Carbon sequestration, while a promising strategy to mitigate climate change, faces several significant challenges:

1. **Economic Barriers**: Implementing carbon sequestration practices can be costly for farmers, requiring investments in new technologies, seeds, and equipment. Financial incentives and subsidies are often necessary to encourage adoption, but these can be difficult to secure and sustain **[95]**.

2. **Knowledge and Education**: There is a substantial gap in knowledge among farmers regarding effective carbon sequestration methods. Education and training programs are essential but can be resource-intensive and slow to implement **[96]**.

3. **Monitoring and Verification**: Accurately measuring and verifying the amount of carbon sequestered is complex and expensive. Reliable monitoring systems are crucial to ensure that sequestration efforts are having the intended impact, but current technologies and methodologies are still developing **[97]**.

4. **Soil and Climate Variability**: The effectiveness of carbon sequestration techniques can vary widely depending on local soil types, climate conditions, and agricultural practices. This variability makes it challenging to predict outcomes and standardize practices across different regions.

5. **Policy and Regulatory Frameworks**: There is often a lack of clear policies and regulatory frameworks to support carbon sequestration. Policymakers need to create robust, consistent guidelines and incentives to encourage widespread adoption **[98]**.

6. **Long-term Sustainability**: Maintaining carbon sequestered in soils over the long term can be difficult. Practices that sequester carbon need to be sustained indefinitely, which requires ongoing commitment and adaptation to changing environmental conditions.

7. **Competing Land Uses**: Land dedicated to carbon sequestration may compete with other land uses, such as food production or urban development. Balancing these competing needs is a complex challenge that requires careful planning and negotiation **[99]**.

8. **Environmental Impact**: While many carbon sequestration practices have positive environmental impacts, some can lead to unintended consequences, such as biodiversity loss or changes in water availability. It's essential to consider and mitigate these potential impacts.

Addressing these challenges requires a multifaceted approach involving technological innovation, supportive policies, and collaboration between scientists, policymakers, and the agricultural community.

Conclusion

In conclusion, while carbon sequestration in agricultural practices presents a promising avenue for mitigating climate change, it is accompanied by a range of challenges that need to be addressed to realize its full potential. Economic barriers, knowledge gaps, and the complexities of monitoring and verification are significant hurdles that require coordinated efforts from policymakers, researchers, and farmers. Additionally, the variability in soil and climate conditions, along with the need for robust regulatory frameworks and sustainable long-term practices, underscores the complexity of this endeavour. Despite these obstacles, the integration of effective carbon sequestration techniques in agriculture holds the promise of enhancing soil health, improving crop yields, and significantly reducing atmospheric carbon levels. By overcoming these challenges through innovation, education, and policy support, agriculture can play a pivotal role in the global effort to combat climate change and promote environmental sustainability.

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